



AIR FORCE RESEARCH LABORATORY

Next Generation, High Accuracy Optical Tracker for Target Acquisition and Cueing

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Abstract

A critical need exists for a fast, cost-effective, six-degrees-of-freedom (6DOF) tracker that is immune to cockpit and helmet scatterers of magnetic/electrical field energy, vehicle vibration, and harsh lighting conditions. Magnetic and inertial tracking technologies each have limitations that make them undesirable as next generation solutions. Optical tracking technologies, while having occlusion problems, are increasingly seen as the more attractive next generation solution. The optical tracker, developed at Ascension to meet these needs, measures the angle of incidence of point radiating emitters mounted on the helmet. The sensors measure angle of incidence in one dimension and two or three sensors are required to be mounted on the cockpit instrument panel to achieve determination of both position and orientation of a helmet. The sensor uses a transmissivity mask, which is located a known distance above a linear detector array surface. The mask consists of three transmissivity frequencies varying in one dimension. Each point radiating emitter illuminates the mask to cast an image onto the array. The array image is read at a high update rate and a remote processor identifies image phases to determine the image shift along the detector array axis. The three frequencies, being sufficiently separate in frequency to determine a coarse absolute image shift, as well as medium and fine image shifts, are used to determine a high-resolution absolute image shift. The image shift of each sensor is used to compute the plane angle of incidence of each emitter. The minimal system configuration includes two sensors and four emitters or three sensors and three emitters. More sensors and emitters may be used to increase tracker motion box. Flight tests were conducted in August and September of 2005. The phasorBIRD prototype was flown in a test aircraft to evaluate the effect of direct sunlight and vibration on accuracy and noise.

1. Introduction

The phasorBIRDTM is a 6DOF optical tracker that uses a camera array and an emitter array to determine position and orientation of one relative to the other. The camera array is composed of two or more detector arrays that are arranged to allow determination of planes of incidence for each emitter source. A divergent point source illuminating a mask with a known pattern in front of the detector projects an image onto the detector array surface. The determination of the lateral pattern shift is used to determine the plane of incidence to the camera. Combining planes of incidence from emitters in the emitter array to cameras in the camera array yields position and orientation of one array relative to the other. Figures 1 and 2 show the camera array and emitter array arranged in evaluation configurations. The evaluation emitter array is merely a rigid adapter for the four individual emitter sources. In a production configuration, individual emitters would be integrated into a hard “instrument shell” attachable to a helmet.

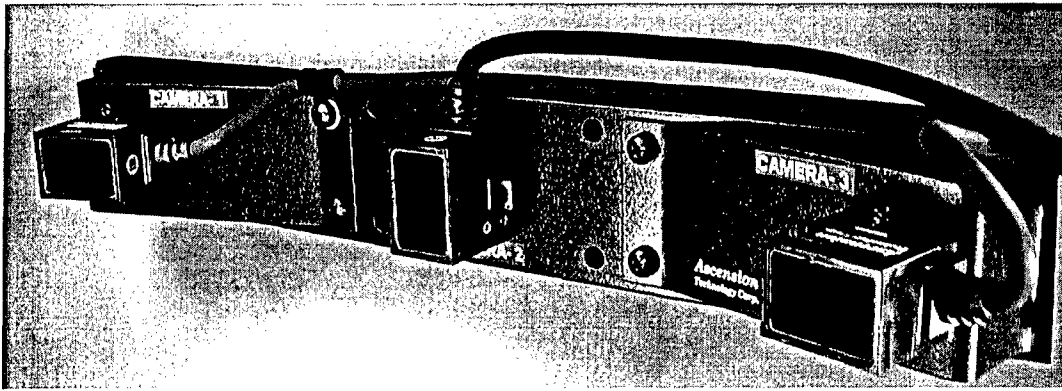


Figure 1. Camera Array

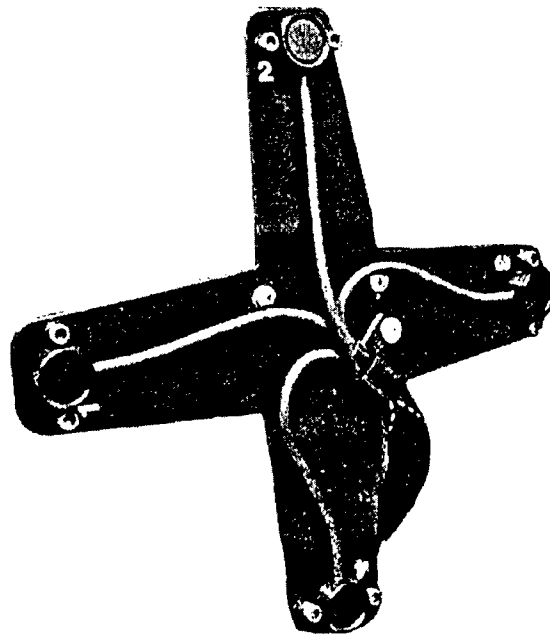


Figure 2. Emitter

The PhasorBIRD could have been implemented using an off-the-shelf linear detector array to receive and decode mask image frequency shift, and the camera prototype employed such a linear detector. However, the linear detector array was found to have certain limitations that proved incompatible in the harsh jet cockpit lighting environments. These were primarily the throughput limitations inherent to linear arrays, and the small active area of linear array pixels having lower signal-to-noise ratio and higher susceptibility to dust and scratches in optical surfaces.

To allow high measurement rate and offer larger detection area for high signal-to-noise ratio, a novel concept was developed that uses a detector array that can decode the phase of each mask image frequency.

2. Helmet Tracker Requirements and Studies

The phasorBIRD™ project arises from the long term need for a high accuracy tracker to be used for helmet tracking in jet cockpit and tank applications, as well as flight simulators and other augmented reality environments. In particular, the key requirements for a military head tracker are:

- Line-of-sight accuracy of 0.1° RMS in the forward viewing area and 0.25° elsewhere.
- Night vision goggle (NVG) compatibility for jet cockpit applications.
- Immunity to high ambient sunlight in cockpit environment.
- Miniature tracker components that fit in a cockpit.
- Helmet mounted sensors/emitters must weigh less than a few ounces.
- No distortion due to a metallic environment that may change.
- Wide field-of-view tracking to follow all pilot head movements.
- Fast update rate (over 300Hz).
- Solid-state technology compatible with a harsh vibration environment.

2.1 NVG Response

A requirement of the phasorBIRD™ optical tracker is NVG compatibility. The requirements for NVG compatibility as specified in MIL-STD-3009 were used as a basis to determine NVG compatibility from emitter radiance estimates.

Testing with actual Night Vision Goggles was employed to demonstrate compatibility. To determine infrared compatibility, the visibility of 980nm laser diodes, 1060nm laser diodes, and 970nm LED were tested. The following image shows 980nm and 1060nm laser images taken by camera through the eye pieces of a lab IR viewer and night vision goggles at maximum gain. Spot intensity is approximately equal to ambient lighting in a cockpit if helmet mounted IR sources were used. There is still some response at 980nm, but at 1060nm there is no response.

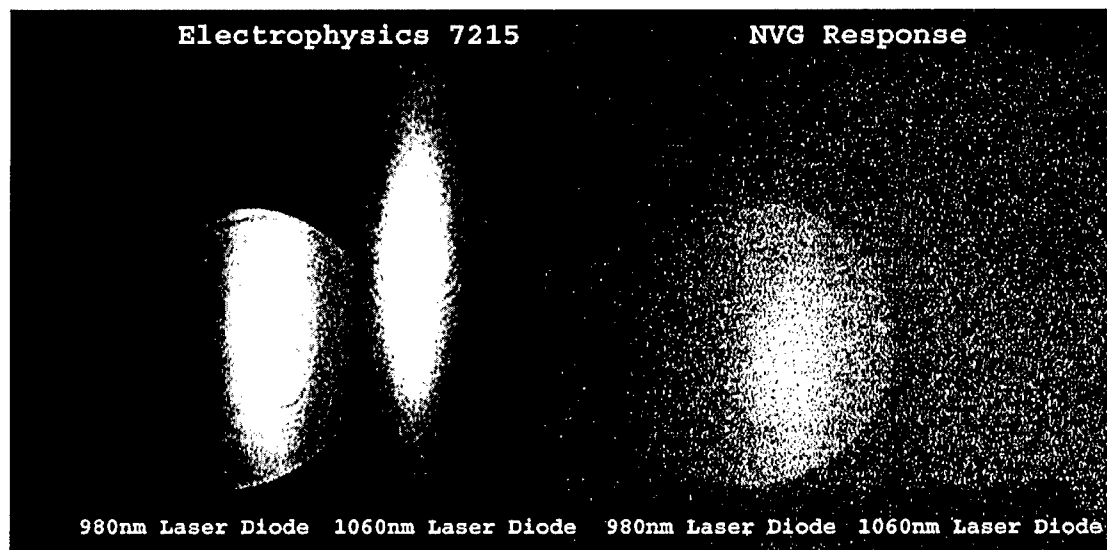


Figure 3. Lab IR viewer and NVG response to 980nm and 1060nm laser diode emission.

Testing of a 970nm LED proved to be less NVG compatible, since the broad LED emission overlaps the responsivity of the NVG in the 930nm region. Filtering of this side band helps, but sharp cut-off filters are generally not available for a wide-angle optical emitting surface as is required.

The preferred emitter is a LED to avoid laser "speckle" or non-uniformity of illumination intrinsic to coherent laser sources. The LED sources unfortunately have wide spectral bandwidths of about $\pm 50\text{nm}$ (Full Width Half Maximum), and to be strictly NVG invisible like the 1060nm laser diode shown in Figure 3, a 1060nm LED would probably be required. The detector design allows for wavelengths including 1060nm for this reason.

As an alternative to Infrared emitters, ultraviolet LED sources were investigated for NVG compatibility. This UV source also emits a small amount of light ($\sim 1\%$) in the visible range and so direct viewing would require a band-pass filter to suppress visible light emission. Another characteristic of UV emitters is fluorescence of materials in view of the emitters. The fluorescence is typically in the 470nm range, but may have some energy in the NVIS spectral sensitivity region.

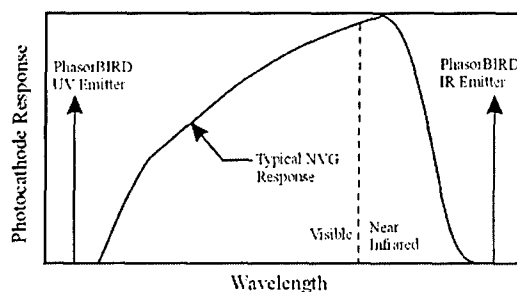


Figure 4. Typical NVG spectrum and phasorBIRD NVG compatible emitters.

2.2 Sunlight Spectrum and Canopy Transmission

The spectral transmission of jet canopies was measured to allow calculation of spectral irradiance of sunlight within the cockpit. Sunlight has been the bane of most optical systems designed to meet helmet-tracking applications, responsible for interference effects, saturation, and detector shot noise. Our objective was to use a lower power UV emitter and have the Polycarbonate canopy act as a filter, rejecting sunlight above the UV wavelength, and allowing the camera filter to accept emitter light in the UV wavelength. Transmissivity scans of several representative canopies, using spectral radiometric equipment, were performed from 200nm to 3000nm as shown in figure 5. The solar irradiance at high altitude was approximated by the AM0 (Air Mass Zero) spectral irradiance curve (figure 6) and the solar radiance transmitted by the canopies is shown in figure 7.

The solar transmissions confirmed that operation below in the UV range would be ideal and that the mid-infrared region might be attractive in reducing sun ambient interference. The solar transmission is significantly reduced beyond the near IR range, but emitters and detectors in this range are costly. Therefore, a solution using lower cost Silicon detectors with response range of approximately 300nm to 1100nm was preferred. UV LED and near IR lasers diodes met this requirement in addition to being NVG compatible. But to make full use of the canopy as a filter, the UV emitter was chosen, allowing almost the complete rejection of sunlight.

It is understood that the scope of applications for this project includes more than cockpit applications that might take advantage of the filtering properties of canopies. To insure that the tracker can work in the environment inside of helicopters and ground based vehicles such as tanks an effort was made to insure robust operation under all sunlight conditions.

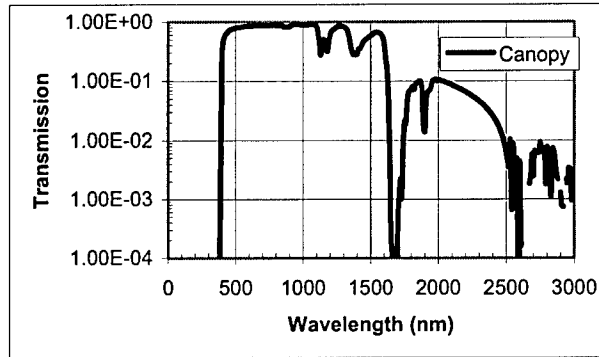


Figure 5. Canopy transmissivity.

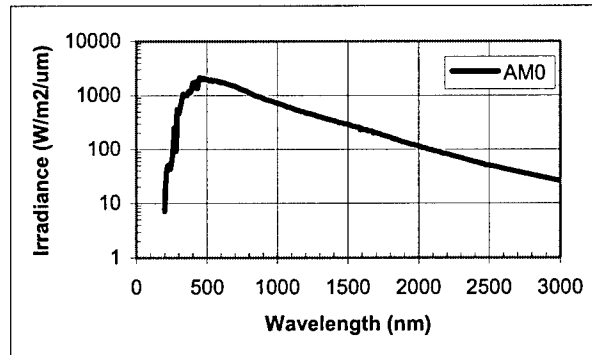


Figure 6. Solar Irradiance (AM0).

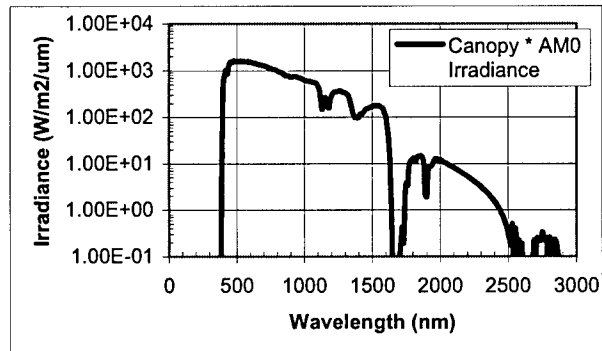


Figure 7. Canopy AM0 transmissions.

2.3 Sun Interference Measurements

Sun interference measurements and simulations were performed to determine whether modulation would be required, and the magnitude and frequency range of sun noise effects. Several types of sun interference and noise were studied, including effects of atmospheric scintillation and detector shot noise due to large sun induced photodetector currents. Figure 8 shows an average magnitude spectrum taken in direct noon sunlight on a clear winter day at ground level at 45° North latitude. This sunlight sample was measured directly using a photodetector. Scintillation noise appears peaked in the 200Hz range with frequency components up to about 2KHz, while shot noise dominates above that frequency. The scintillation magnitudes are quite variable, having relatively quiet periods and very noisy periods with amplitudes in the 200Hz range varying over an order of magnitude. No attempt was made to measure or simulate worst-case effects such as flying through clouds, however helicopter rotor modulation of the sun was simulated and determined to have significant frequency content up to 100KHz.

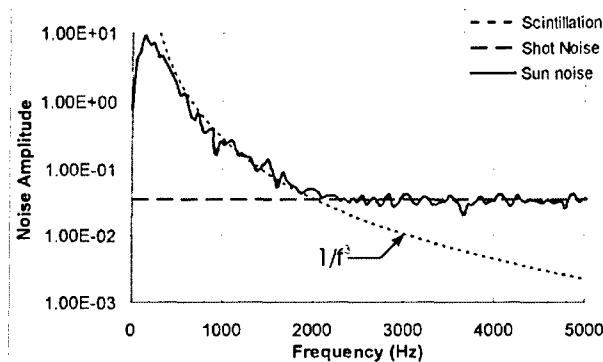


Figure 8. Sun Noise

We determined that off-the-shelf linear detector arrays would not allow a fast enough signal sampling rate to avoid some of the low frequency sun interference effects such as atmospheric scintillation, nor would it avoid the higher frequency interference sources likely to be experienced at flying speed and altitude. In addition, full sun shot noise was significant for situations where canopy filtering was not available. To provide a robust sensor technology in these harsh ambient lighting conditions, a large area detector was required to reduce shot noise and sensitivity to dust and scratches, and modulation of the emitters was required to reject large amplitude, lower frequency sun light interference.

3. phasorBIRD Principle of Operation

The phasorBIRD sensor measures angle of incidence between a point source emitter and an optical sensor comprising a coded mask with underlying detector to receive the mask image. Decoding the image allows us to determine the image displacement to a high degree of accuracy, and from this, the angle of light incidence. Figure 9 illustrates an emitter casting a mask image onto a detector array. The mask is comprised of three spatial transmission frequencies, the fundamental (f_1), a fifth harmonic (f_5), and a 25th harmonic (f_{25}).

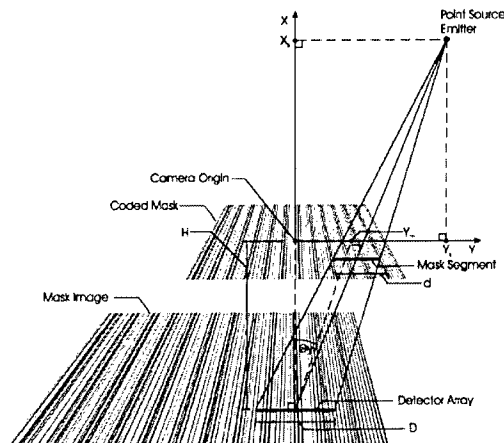


Figure 9. phasorBIRD principle of operation.

Figure 10 shows a bitmap image of the mask and a graphical representation of the constituent mask frequencies f_1 , f_5 , and f_{25} .

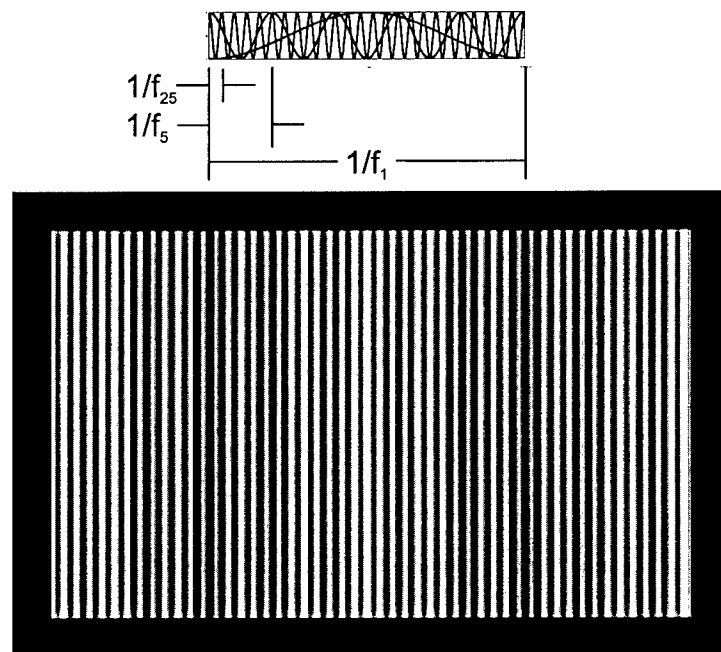


Figure 10. Mask pattern.

To receive the transmitted mask image a detector array was designed that allowed each sinusoid to be detected. Measurement of the phase of the fundamental frequency component is used to determine a coarse position and the particular cycle of the fifth harmonic frequency component. In this same manner, the phase of the 5th harmonic is used to determine the detector position to a finer degree and the particular cycle of the 25th harmonic component leading to the exact pattern shift and the angle of incidence between the point source of radiation. This methodology allows one to measure incidence angles with an accuracy of a few thousandths of a degree.

3.2 Camera Sensor Design

The phasorBIRD camera sensor shown in Figure 11 is a planar construction consisting of a UV filter, a masked glass window, aperture, window frame, and detector substrate with detector and preamp electronics. The planar construction, using materials with good thermal stability was key to the design success. The sensor dimensions are 28mm L x 18mm W x 14mm H. The camera overall dimensions are 32mm L x 22mm W x 27.5mm H and the weight is 1.47 oz.

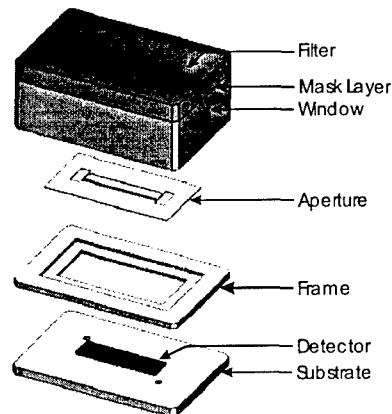


Figure 11. Camera sensor construction.

4. Flight Test

Three flight tests were conducted in August and September of 2005. The phasorBIRD prototype was flown in a test aircraft to evaluate the effect of direct sunlight and vibration on accuracy and noise.

Figures 12, 13, and 14 show the system setup in the airplane. The left-side aft cargo doors were removed and replaced with an acrylic window that mimicked the solar irradiance illuminating the cameras at altitudes reached during tactical flights.

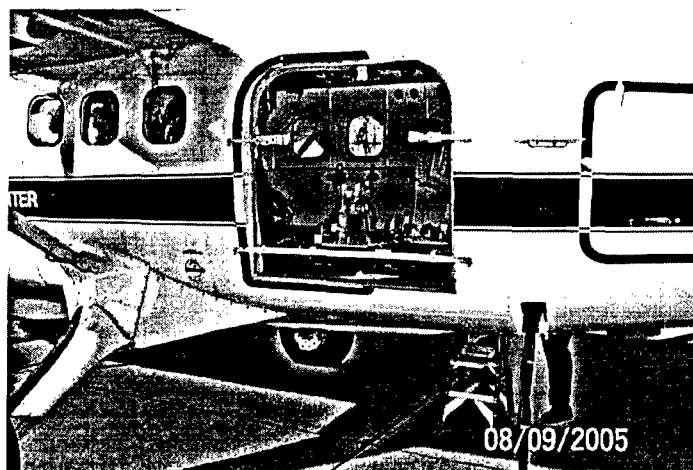


Figure 12. Bay window

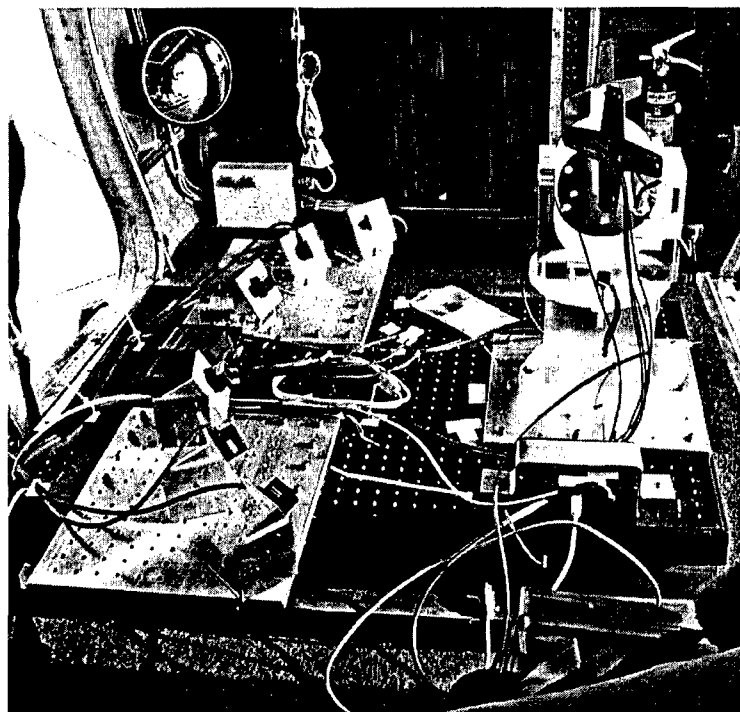


Figure 13. phasorBIRD in the airplane.



Figure 14. phasorBIRD emitter arrays on the gimbal

PhasorBIRD position and line-of-sight (LOS) static accuracy and noise were evaluated under three different ambient conditions:

- Pre-Flight session. Airplane in the hangar, no direct sunlight, no vibration
- On Sun session. Airplane in the air, maximum exposure of the cameras to sunlight, vibration
- No Sun session. Airplane in the air, no direct sunlight through the window, vibration

During each session the gimbal, with emitter arrays, was rotated through a sequence of known orientations. Position and orientation data computed by the phasorBIRD were collected at every gimbal orientation. A variety of orientations within a range representing pilot head-motion was used. This range was defined to be:

- $\pm 90^\circ$ in azimuth
- -30° to $+60^\circ$ in elevation
- $\pm 45^\circ$ in roll

Comparison of the On Sun session results to the Pre-Flight and No Sun results shows that sun has no effect on phasorBIRD position and LOS static accuracy or noise.

5. Conclusions

The phasorBIRD optical system has resulted in the development of a high accuracy optical tracker based on a novel angle of incidence sensor. The technology has shown itself to be robust in the harsh jet cockpit environment, which has foiled most previous attempts to design an optical helmet tracker. Aircraft testing has shown that accuracy and noise are not affected by sunlight. This program has resulted in the most accurate head tracker developed to date over the 40 year development and test history of mechanical, optical, acoustic, and electromagnetic trackers for military use.